CM Aprvd ISSUED 2008/12/09

911135
Revision 0

ENGINEERING SERVICES FOR THE NEXT GENERATION NUCLEAR PLANT (NGNP) WITH HYDROGEN PRODUCTION

Test Plan for the Reactor Core Assembly

Prepared by General Atomics
For the Battelle Energy Alliance, LLC

Subcontract No. 00075309
Uniform Filing Code UFC:8201.3.1.2

GA Project 30302

GENERAL ATOMICS

GA 1485 (REV. 08/06E)

ISSUE/RELEASE SUMMARY

☐ R & D ☐ DV&S ☒ DESIGN ☐ T&E ☐ NA	APPVL LEVEL	DISC	QA LEVEL	SYS	DOC. TYPE	PROJECT	DOCUMENT NO.	REV
	5	N	I	11	RPL	30302	911135	0

TITLE:
Test Plan for the Reactor Core Assembly

CM APPROVAL/ DATE	REV	PREPARED BY	APPROVAL(S) ENGINEERING	QA	PROJECT	REVISION DESCRIPTION/ W.O. NO.
	0	M. Richards	A. Shenoy	K. Partain	J. Saurwein	Initial Issue A30302-0130

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* See list of effective pages

NEXT INDENTURED DOCUMENT(S)
N/A

COMPUTER PROGRAM PIN(S)
N/A

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ACRONYMS AND ABBREVIATIONS

ASTM	American Society of Testing and Materials
CTF	Component Test Facility
DDN	Design Data Need
DOE	U.S. Department of Energy
FSV	Fort Saint Vrain
GA	General Atomics
GT-MHR	Gas Turbine Modular Helium Reactor
HTGR	High-Temperature, Gas-Cooled Reactor
HTTR	High Engineering Test Reactor
INL	Idaho National Laboratory
ISI	In-Service Inspection
JAEA	Japan Atomic Energy Agency
MHR	Modular Helium Reactor
MHTGR	Modular HTGR
NDE	Non-Destructive Examination
NP-MHTGR	New Production Modular HTGR
ORNL	Oak Ridge National Laboratory
RT	Room Temperature
TRL	Technology Readiness Level
VHTR	Very High Temperature Reactor

1 INTRODUCTION

The graphite components of the reactor are the permanent side reflector, the core support structure and the core. The core includes the fuel elements and the replaceable reflector elements. For the General Atomics (GA) commercial Gas Turbine Modular Helium Reactor (GT-MHR) the reference material for the core, permanent side reflectors, and the core support was H-451 graphite, which is no longer commercially available. The reference material for the permanent side reflector support blocks at the hot duct entrance and selected core support post blocks is a purified form of HLM grade graphite. Figure 1-1 shows the GT-MHR core assembly and support structure. Figure 1-2 shows horizontal cross section of the core assembly at mid-plane and Figure 1-3 shows a vertical cross section of the core assembly and support structure. Figure 1-4 shows a standard GT-MHR fuel element. A complete description of the GT-MHR core assembly and support structure graphite components is given in [Phelps 2008].[1] The final design of the core assembly and support structure for a block-type Next Generation Nuclear Plant (NGNP) is expected to be similar to that of the GT-MHR.

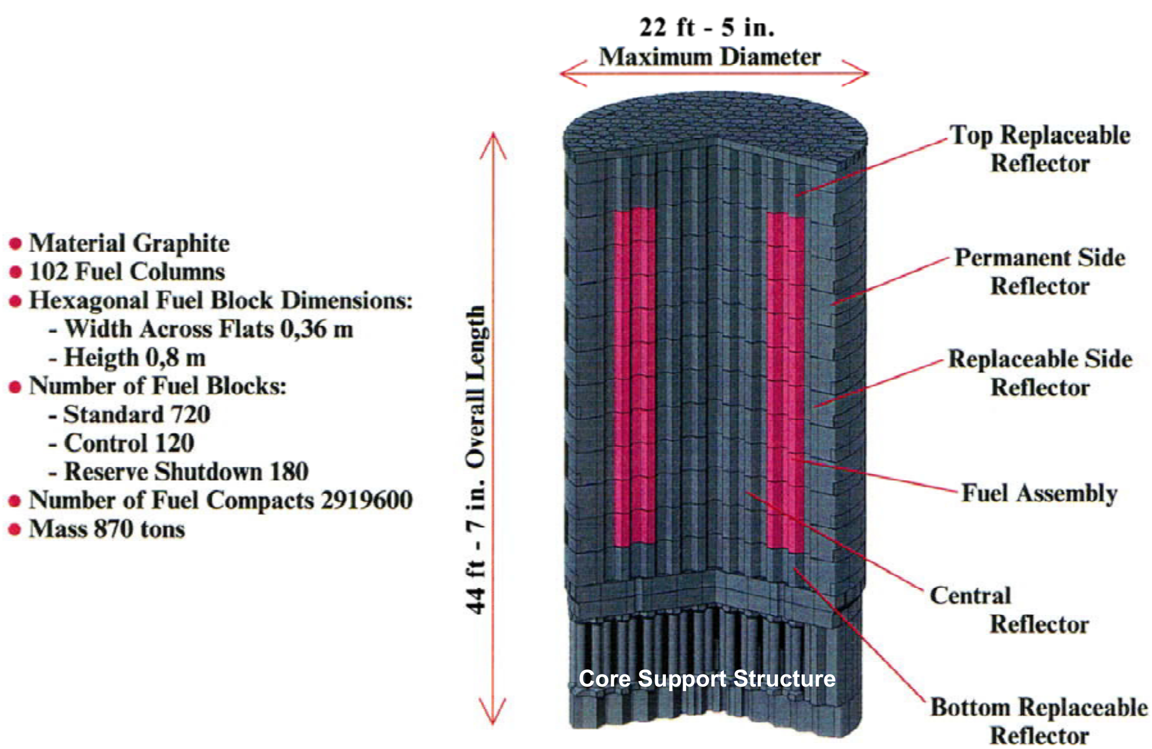

Figure 1-1. GT-MHR Core Assembly and Support Structure

[1] A listing of applicable documents for this Test Plan is provided in Section 2.

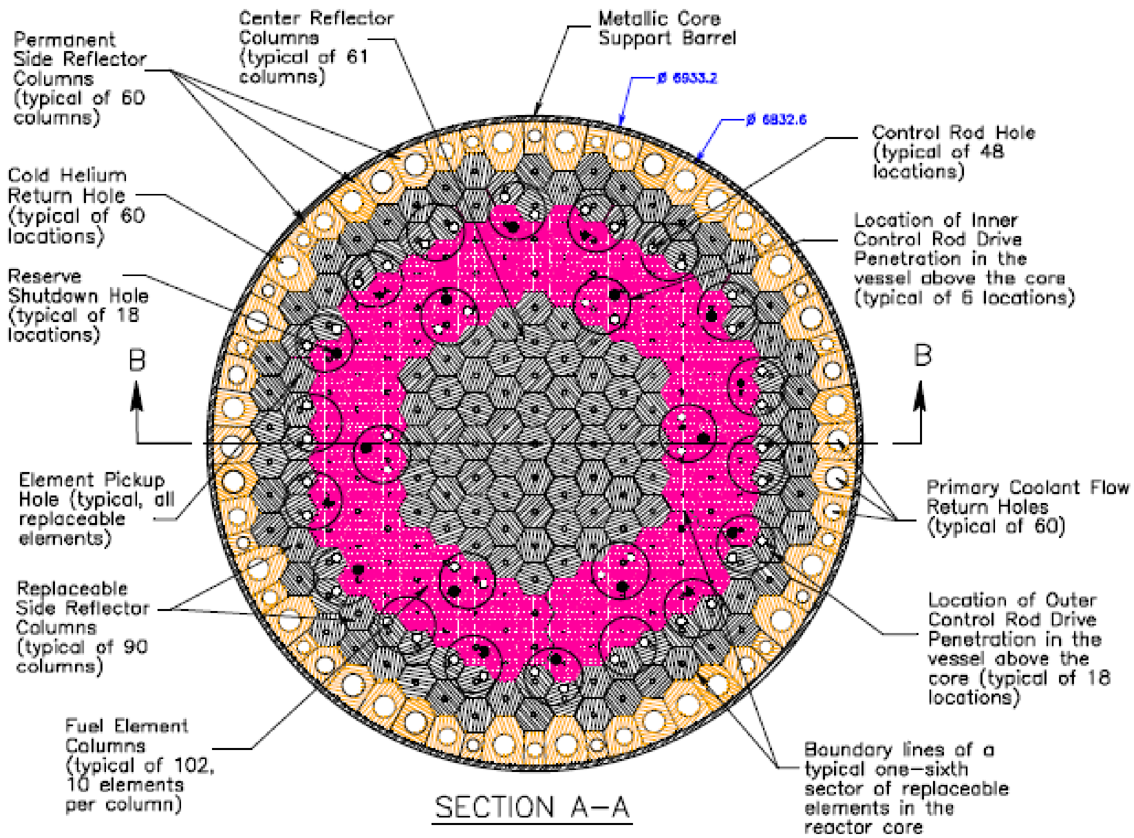

Figure 1-2. Horizontal Cross Section through the Reactor Core and Mid-Plane

Both graphite grades of selected billet sizes were used successfully in the Ft. St. Vrain (FSV) reactor, and much is known about these materials. However, the NGNP design conditions are different from those in previous reactors such as FSV and other large HTGRs. Specifically for the NGNP, designing for conduction cooldown events requires graphite properties at higher temperatures, and the currently proposed structural design criteria require new material properties to be measured, and test data used to validate the design.

Due to changes in the graphite manufacturing industry, graphite made by different suppliers and from new sources of raw materials must be characterized by testing before they can be qualified for use in the NGNP. Consequently, a high-priority for the NGNP is to identify and qualify a near isotropic graphite to replace grade H-451.

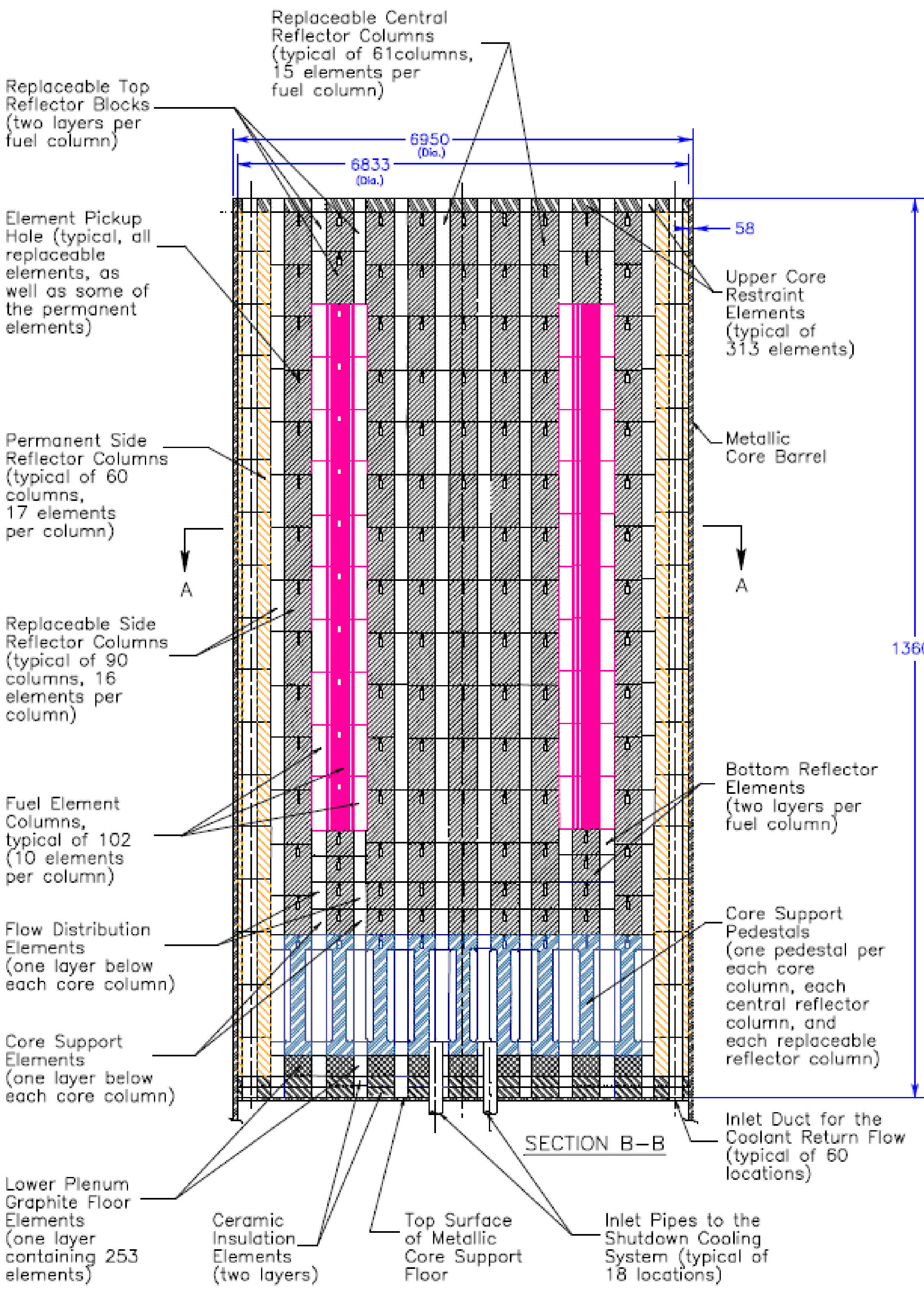

Figure 1-3. Vertical Cross Section through the Reactor Core

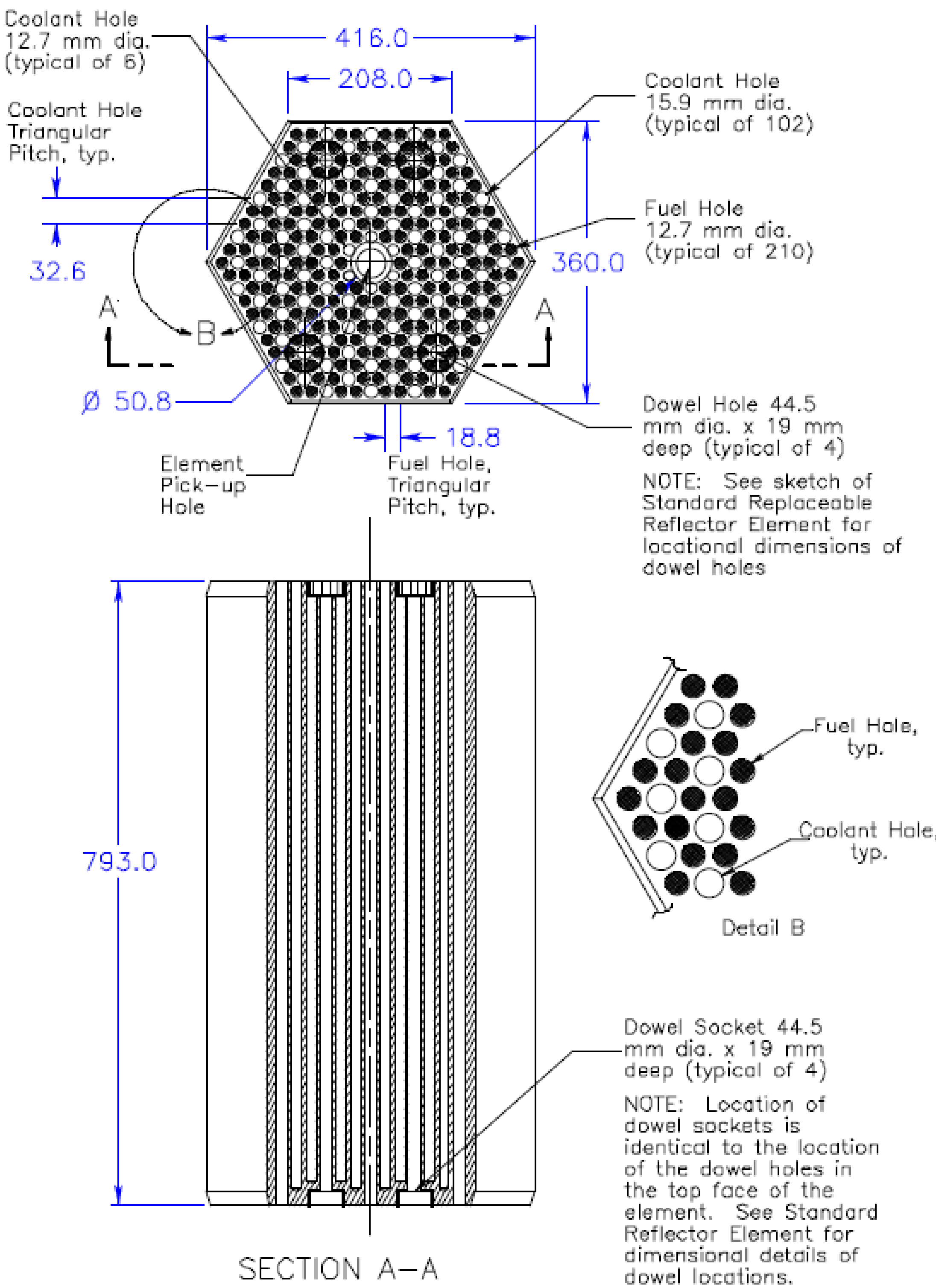

Figure 1-4. Standard GT-MHR Fuel Element

1.1 Scope

The scope of this Test Plan includes the fuel element graphite blocks, replaceable inner and outer reflector elements, upper reflector elements, and lower reflector elements (including flow distribution elements). All of these elements are hexagonal-shaped blocks manufactured from the same nuclear-grade graphite. The scope of this test plan is limited to testing on full-size (or scaled) elements and assemblies of elements Testing performed on graphite specimens to obtain property data is within the scope of the Test Plan for the Reactor Graphite Elements.

The permanent side reflector and core support structure graphite components are part of the Reactor Internals, but are not within the scope of this Test Plan. These components are subjected to less severe conditions of temperature and neutron fluence and generally have different design requirements than graphite elements that comprise the core and replaceable reflectors.

1.2 Purpose

The purpose of this Test Plan is to define the test programs that will raise the Technology Readiness Level (TRL) level for Reactor Core Assembly from 5 to 7.

The primary functions of the Reactor Core are to generate high temperature heat using nuclear fission, transfer the heat to the helium coolant, and control radiation from the core. The Reactor Core consists of fuel elements, inner and outer reflector elements, upper reflector elements, and lower reflector elements (including flow distribution elements). All of these elements are hexagonal-shaped blocks manufactured from nuclear grade graphite. In terms of SSC categorization, the permanent side reflector is assumed to be part of Reactor Internals. The principal fuel elements are in the form of a right hexagonal prism, 793 mm high and 360 mm across the flats. The two other types of fuel elements are those with control-rod channels and those with reserve-shutdown channels. The active core (fueled region) consists of 102 fuel columns with 10 blocks per column, comprising a 3-row annular region. The active core is surrounded by prismatic blocks that form the upper, lower, inner, and side reflectors. Some of the columns in the outer reflector and active core (and possibly the inner reflector, depending on the final core design) contain channels for controls rods. Some of the columns in the active core also contain channels for reserve shutdown material.

The testing programs to support design of the Ft. St. Vrain (FSV) reactor and the operational data base from FSV justify a high TRL level for this system. However, FSV used grades H-327 and H-451 graphite that are no longer available and the NGNP prismatic core design will likely adopt one of the new grades of graphite that are under development (e.g., PCEA, NBG-17 or NBG-18), as described in the NGNP Graphite Technology Development Plan prepared by INL. In addition, the NGNP core configuration is significantly different from FSV (annular core for

NGNP vs. cylindrical core for FSV and 10-block high core for NGNP vs. 6-block high core for FSV). For these reasons, the starting TRL level is judged to be 5 for this system.

A TRL of 6 is achieved after the requisite design data have been obtained for individual fuel elements. These data are specified in the following Design Data Needs (DDNs):[2]

C.11.03.03, Core Element Dynamic Strength Data

C.11.03.04, Core Element Failure Mode Test

C.11.03.41, Fuel Element Channel Flow Data

C.11.03.42, Control Rod Flow Channel Data

JAEA Comments on Advancement to TRL-6

Based on their experience with the HTTR and IG-110 graphite, JAEA provided the following comments with regard to advancement to TRL-6:

Integrity of the graphite components should be verified using detailed stress analyses with finite-element computer codes, accounting for the irradiation effects on graphite properties.

A TRL of 7 is achieved after the requisite design data have been obtained for mock-up testing involving multiple graphite components. These data are specified in the following Design Data Needs (DDNs):

C.11.03.01, Core Column Vibration Data
C.11.03.45, Core Crossflow Test Data
C.11.03.46, Core Fluctuation Test Data
C.11.03.43, Bottom Reflector/Core Support Pressure Drop and Flow Mixing Data
C.11.03.44, Metallic Plenum Element and Top Reflector Pressure Drop and Flow Distribution

JAEA Comments on Advancement to TRL-7

Based on their experience with the HTTR and IG-110 graphite, JAEA provided the following comments with regard to advancement to TRL-7:

1. The integrity of the core graphite components should be confirmed in sufficiently large engineering-scale, fully-mocked up core tests. Mechanical tests on the components, including buckling of support post and fracture of keys and key ways are necessary to demonstrate integrity. Integrity under realistic seismic loads is also needed.

[2] The protocol for assigning DDN numbers is described in the NGNP Umbrella Technology Plan [Hanson 2007].

2. ASME design criteria are currently under development for nuclear-grade graphite. These design criteria must be completed prior to validating the graphite component design. The ASME design criteria should include acceptance criteria for allowable defects in graphite components. Non-destructive test methods (e.g., eddy current and ultrasonic testing) should be developed to measure defects with respect to the acceptance criteria.

3. The capability to insert of control rods into the reactor core under accident conditions should be verified, including abnormal displacement or misalignment of the core graphite blocks.

4. The capability to cool the control rod drive mechanism and the in-core columns of control rods will be verified by test and analysis of the flow distribution and heat transfer characterisitics in a mock-up core sturcture at high temperature and pressure.

5. The integrity of the graphite components should be validated by in-service inspection (ISI). The ISI surveillance test methods, items, and frequency should be determined considering the in-core configuration and reactor operation plan, based on previous HTTR experience [JAEA 2007].

To achieve a TRL of 8, instrumented tests are performed as part of NGNP startup testing to confirm flow distributions, temperature distributions, and mechanical loadings are within design specifications.

2 APPLICABLE DOCUMENTS

[GDDM 1984]	“Graphite Design Data Manual,” MAN 906374, Rev. A, General Atomics, San Diego, CA, August 1984.
[Hanson 2007]	“NGNP Umbrella Technology Development Plan,” PC-000543, Rev. 0, General Atomics, San Diego, CA, July 2007.
[Hayner 2005]	“Next Generation Nuclear Plant Materials Research and Development Program Plan,” INL/EXT-05-00758, Rev. 2, Idaho National Laboratory, Idaho Falls, ID, September 2005.
[JAEA 2006]	“Characteristics of First Loaded IG-110 Graphite in HTTR Core,” JAEA-Technology 2006-048, Japan Atomic Energy Agency, Tokai, Japan, September 2006.
[JAEA 2007]	J. Sumita et al., JAEA-Data/Code 2007-001, Japan Atomic Energy Agency, Oarai, Japan.
[Luci 1993a]	“Reactor Graphite Technical Development Status Report,” CEGA-002817, Rev. 1, General Atomics, San Diego, CA, October 1993.
[Luci 1993b]	“450 MW(t) MHTGR Reactor Graphite and Ceramics Development Plan,” DOE-HTGR-90358, General Atomics, San Diego, CA, June 1993.
[Morrison 1993]	“Graphite Material Specification for NP-MHTGR Fuel and Reflector Elements,” CEGA-001803, Rev. 1, General Atomics, San Diego, CA, April 1993.
[Phelps 2008]	“Graphite Block Requirements for the GT-MHR Core,” RDE 911116, Rev. 0, General Atomics, San Diego, CA, February 2008.
[Windes 2007]	“Graphite Technology Development Plan,” PLN-2497, Rev. 0, Idaho National Laboratory, Idaho Falls, ID, October 2007.
[Betts 1988a]	“MHTGR Core Flow-Induced Vibration Test Plan,” DOE-HTGR-88124, Rev. 0, General Atomics, San Diego, CA, September 1988.
[Betts 1988b]	“MHTGR Core Fluctuation Test Plan,” DOE-HTGR-88123, Rev. 0, General Atomics, San Diego, CA, September 1988.

3 TEST PLAN FOR ADVANCEMENT FROM TRL 5 to TRL 6

This Test Plan is organized according to Design Data Need. The required data need to be obtained for the reactor service conditions during normal operation and accident conditions. These conditions are defined in the NGNP Umbrella Technology Development Plan [Hanson 2007] and include temperature, pressure, fast neutron fluence, and coolant impurity levels. For some tests, it may be impractical to obtain data under the specified NGNP conditions, and methodologies to extrapolate the data from test conditions to reactor conditions must be developed before the specific Test Specifications and Test Plans are approved.

3.1 Core Element Dynamic Strength Data (DDN C.11.03.03)

3.1.1 Test Objective

The replaceable graphite core elements must be able to withstand the dynamic stresses due to seismic loads in combination with the thermal and irradiation stresses. The failure load, and stiffness of the core elements subjected to dynamically applied forces is required. The contact time and coefficient of restitution must be measured for correlation with analysis methods and input into seismic analysis. The objective of this test is to obtain dynamic strength data for the purpose of validating computer codes and methods.

3.1.2 Test Description

The failure load and failure mode of virgin fuel elements under mechanical loads were measured in development programs. Some analytical correlations were performed, but these did not include crack progression analyses. Limited cracking under thermal/irradiation stresses have been observed in two FSV fuel elements and reasonably good analytical correlations were achieved. The cracking was, however, far from extensive enough to represent failure in a functional sense.

To determine the failure load, stiffness, coefficient of restitution and contact time a horizontal drop or pendulum device may be used to apply different dynamic forces to the core element test component. Failure load will be determined by increasing the dynamic load until the test component fails. Stiffness is determined by measuring the deformation (bending, stretching or compression of the test element). To determine the stiffness dynamic forces will be applied to the test piece and the deformation will be measured. The coefficient of restitution is the ratio of the velocity of two objects before and after collision. This will be determined by measuring the velocity of the impact device and the test piece before and after the collision. The contact time is the amount of time that the test fixture impact device is in contact with the test piece during the dynamic collision. The test fixture will be instrumented to provide the desired test data.

3.1.3 Test Conditions

The test will be performed on unirradiated elements under ambient conditions. The maximum relative impact velocity between core elements shall be 1.5 m/s.

3.1.4 Test Configuration/Set-Up

A section of core elements will be configured to allow testing in horizontal drop or a pendulum test apparatus. The test device shall have appropriate instrumentation and a data acquisition system that allow fast test data turnaround and accurate measurement and data capture. Where applicable, appropriate ASTM standards will be used.

3.1.5 Test Duration

24 months, including preparation of all test documentation

3.1.6 Proposed Test Location

The testing could be performed at GA, the Component Test Facility (CTF), a National Laboratory, or at a commercial material testing facility.

Commercial Material Testing Laboratory Contact:
Westmorland Mechanical Testing and Research Inc.
221 Westmoreland Drive
Youngstown, PA 15696-0388
Phone: (724) 537-3131
Fax: (724) 537-3151
Email: admin@wmtr.com

3.1.7 Measured Parameters

The failure load and stiffness data of core graphite elements subjected to dynamically applied forces is needed under the service conditions given in the NGNP Umbrella Technology Development Plan [Hanson 2007]. The contact time and coefficient of restitution must be measured for correlation with analysis methods and input to seismic analysis. The nature of the forces and their duration must be representative of the type of loads imposed on the fuel elements during earthquakes.

3.1.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for

Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.”

3.1.9 Test Evaluation Criteria

The data base must be sufficient to establish that the mean values of the experimentally determined failure loads are higher than the corresponding analytical predictions.

3.1.10 Test Deliverables

Deliverable	Responsibility
Test Specification	Design Organization
Test Plan	Technology Organization
Test Procedures	Technology Organization
Pre-Test Prediction Report	Design Organization
Test Status Reports	Technology Organization
Test Report	Technology Organization
Test Evaluation Report	Design Organization

3.1.11 Cost, Schedule, and Risk

Cost (2008 $K): 350

Schedule: Final data are needed 24 months after start of final design.

Risk

In the absence of obtaining Core Element Dynamic Strength Data, the design alternatives are: (1) redesign the core to reduce the seismic impact loads on the core elements, which would require keying or clamping of the core; (2) proceed on the basis of the present analytical methods with data from previous tests which were for different material and geometry; (3) isolate the graphite core or reactor vessel to minimize the core seismic loads; and (4) perform strength and stiffness testing on both irradiated and unirradiated elements.

The selected approach is to validate by test using unirradiated core elements the dynamic strength and stiffness predicted by finite element analysis and obtain the properties of irradiated elements by scaling from irradiation tests on elemental material specimens. In addition, validate by test the contact time and coefficient of restitution. This is seen as the most cost effective approach. Alternative 1 would result in a costlier design and more complicated refueling. Alternative 22 would incur the risk of rejection during safety evaluations. Alternative 3 would result in additional development needs and higher cost. Alternative 4 was rejected because of the difficulty involved in obtaining irradiated elements for test purposes and also the costs and difficulty involved in testing irradiated elements.

Without dynamic test data, design alternative 2 would be used, with the risk of rejection during safety evaluation, which may result in either a crash technology program or a late design change.

3.2 Core Element Failure Mode Test (DDN C.11.03.04)

3.2.1 Test Objective

The steps in the design process for meeting the plant availability and component safety and reliability requirements includes calculations of how a crack, if initiated, would progress until the core element is functionally damaged. The methods for performing these calculations need validation. The objective of this test is to obtain data to validate these methods.

3.2.2 Test Description

The failure load and failure mode of virgin fuel elements under mechanical loads will be measured. The static test is used as a basis for establishing crack initiation and progression correlations with the analytical finite element codes. Testing shall be done with unirradiated elements, and failure loads shall be obtained based on creep effects and changes in mechanical properties as determined in irradiated specimens.

3.2.3 Test Conditions

The test will be performed on unirradiated elements under ambient conditions.

3.2.4 Test Configuration/Set-Up

To be determined by the Technology Organization. Where applicable, appropriate ASTM standards will be used.

3.2.5 Test Duration

24 months, including preparation of all test documentation

3.2.6 Proposed Test Location

The testing could be performed at GA, the Component Test Facility (CTF), a National Laboratory, or at a commercial material testing facility.

Commercial Material Testing Laboratory Contact:
Westmorland Mechanical Testing and Research Inc.
221 Westmoreland Drive
Youngstown, PA 15696-0388
Phone: (724) 537-3131
Fax: (724) 537-3151
Email: **admin@wmtr.com**

3.2.7 Measured Parameters

The failure loads and failure modes are needed for replaceable graphite core elements subjected to the combination of statically applied mechanical and thermal loads which simulate the most severe stress conditions for the service conditions given in the NGNP Umbrella Technology Development Plan [Hanson 2007].

The specific data needed are:

- Laterally applied mechanical load at crack initiation
- Location of crack initiation
- Mechanical load at ultimate failure based on the crack width and crack length failure criteria.
- Crack path from initiation to ultimate failure.

3.2.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.2.9 Test Evaluation Criteria

The data base must establish that the mean values of the experimental data are higher than the corresponding analytical predictions.

3.2.10 Test Deliverables

Deliverable	Responsibility
Test Specification	Design Organization
Test Plan	Technology Organization
Test Procedures	Technology Organization

Pre-Test Prediction Report	Design Organization
Test Status Reports	Technology Organization
Test Report	Technology Organization
Test Evaluation Report	Design Organization

3.2.11 Cost, Schedule, and Risk

Cost (2008 $K): 350

Schedule: Final data are needed 24 months after start of final design

Risk

In the absence of obtaining Core Element Failure Mode Data, the design alternative is to validate the analytical predictions on the basis of the existing data. The selected approach is to perform cracking analysis with finite-element codes as a part of the design process for showing compliance with the plant availability goal and component safety and reliability requirements and to validate the analytical methods by correlation with an expanded test data base. Without an expanded test data base, the design alternative would be used, with the risk that the validation would be deemed unacceptable, resulting in either a crash technology program or a late design change.

3.3 Fuel Element Channel Flow Data (DDN C.11.03.41)

3.3.1 Test Objective

The objective of this test is to obtain friction factor data for representative graphite elements with drilled coolant holes.

3.3.2 Test Description

A representative piece or pieces of graphite will have coolant holes drilled into it. The drilled coolant holes will have dimensions and surface finish to meet the design requirements. An air source will be connected to the graphite test component. The air mass flow will be varied to yield Reynolds numbers between 500 and 100,000. Experimental pressure data will be taken at an initial and downstream location. The air mass flow and air temperature will also be measured.

3.3.3 Test Conditions

The test will be performed in air at ambient conditions over the Reynolds number range 500 – 100,000.

3.3.4 Test Configuration/Set-Up

The graphite test components will consist of thick walled graphite tubes. The tube length and channel hole dimensions will be full scale. The machining parameters for each tube will be defined prior to testing. These parameters include the channel diameter, drill feed rate, bit sharpening frequency, bit replacement frequency and location of coolant channel in the block and block to block variations. It is estimated that approximately 150 tests will be required to envelope the test parameter cases. For each tube, porosity measurements will be made to determine if the tube exteriors need to be coated to prevent permeable flow through the graphite.

The graphite tube will be connected to the to the air flow source. The air flow source will have a variable speed electric drive motor to allow varying air flow rates. The air mass flow will be varied to yield Reynolds numbers between 500 and 100,000. Pressure sensors will be located at the inlet of the test section and at a downstream location. Air stream temperature will measured at the entry and exit locations from the graphite test component. Where applicable, appropriate ASTM standards will be used.

3.3.5 Test Duration

24 months, including preparation of all test documentation

3.3.6 Proposed Test Location

The testing could be performed at GA, the Component Test Facility (CTF), or a National Laboratory.

3.3.7 Measured Parameters

- Air mass flow rate
- Air flow temperature in the fuel channel at the inlet and downstream locations
- Air pressure in the fuel channel at the inlet and downstream locations
- Pressure profile along the tube

3.3.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.”

3.3.9 Test Evaluation Criteria

The data base must be sufficient such that the friction factors can be estimated with an accuracy of [± 10%] at [95%] confidence.

3.3.10 Test Deliverables

Deliverable	Responsibility
Test Specification	Design Organization
Test Plan	Technology Organization
Test Procedures	Technology Organization
Pre-Test Prediction Report	Design Organization
Test Status Reports	Technology Organization
Test Report	Technology Organization
Test Evaluation Report	Design Organization

3.3.11 Cost, Schedule, and Risk

Cost (2008 $K): 350

Schedule: Final data are needed 24 months after start of final design.

Risk

In the absence of obtaining Fuel Element Flow Channel Data, the design alternative is to continue to rely on the current data base. The selected approach is to determine the friction factors by testing. Better knowledge of the coolant channel friction factor will reduce the uncertainty in the core pressure drop and distribution of flow between the coolant channels and control rod channels. Better data in the transitional flow regime will improve predictions of laminar flow instabilities which can result in fuel damage at low power operation. With this information the flow requirements at low power can be minimized. Consequences of using the design alternative are higher fuel temperatures and graphite stresses, and higher flow requirements during refueling, shutdown, and startup operation.

3.4 Control Rod Flow Channel Data (DDN C.11.03.42)

3.4.1 Test Objective

The objective of this test is to obtain friction factor and loss coefficient data for representative control rod graphite elements.

3.4.2 Test Description

Flow tests will be performed on control rod elements with configurations representing both inserted and withdrawn control rods. The test elements will have dimensions and surface finish to meet the design requirements. An air source will be connected to the graphite test component. The air mass flow will be varied to yield Reynolds numbers between 1,000 – 100,000 (rod withdrawn) and 500 – 30,000 (outer annulus, rod inserted). Experimental pressure data will be taken at an initial and downstream location. The air mass flow and air temperature will also be measured.

3.4.3 Test Conditions

The test will be performed in air at ambient conditions over the Reynolds number range indicated above.

3.4.4 Test Configuration/Set-Up

The air flow source will have a variable speed electric drive motor to allow varying air flow rates. The air mass flow will be varied to yield Reynolds numbers between 500 and 100,000. Pressure sensors will be located at the inlet of the test section and at a downstream location. Air stream temperature will measured at the entry and exit locations from the graphite test component. Where applicable, appropriate ASTM standards will be used.

3.4.5 Test Duration

24 months, including preparation of all test documentation

3.4.6 Proposed Test Location

The testing could be performed at GA, the Component Test Facility (CTF), or a National Laboratory.

3.4.7 Measured Parameters

- Air mass flow rate
- Air flow temperature in the fuel channel at the inlet and downstream locations
- Air pressure in the fuel channel at the inlet and downstream locations
- Pressure profile along the tube

3.4.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for

Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

3.4.9 Test Evaluation Criteria

The data base must be sufficient such that the friction factors and loss coefficients can be estimated with an accuracy of [± 10%] at [95%] confidence.

3.4.10 Test Deliverables

Deliverable	Responsibility
Test Specification	Design Organization
Test Plan	Technology Organization
Test Procedures	Technology Organization
Pre-Test Prediction Report	Design Organization
Test Status Reports	Technology Organization
Test Report	Technology Organization
Test Evaluation Report	Design Organization

3.4.11 Cost, Schedule, and Risk

Cost (2008 $K): 350

Schedule: Final data are needed 24 months after start of final design.

Risk

In the absence of obtaining Control Rod Flow Channel Data, the design alternative is to continue to rely on the current data base. The selected approach is to determine the friction factors and loss coefficients by testing. These tests will ensure adequate flow, without excess flow. This will reduce the control rod channel flow requirement necessary to ensure acceptable control rod temperatures. Lowering the control rod channel flow requirement increases the fuel element coolant channel flow, thus reducing fuel temperatures. Lower control rod channel flow also reduces control block stresses and the potential for flow induced vibrations. Consequences of using the design alternative are greater potential for control rod flow-induced vibrations which must be considered in the control rod design, and increased stresses in the control rod blocks and temperatures in the fuel blocks.

4 TEST PLAN FOR ADVANCEMENT FROM TRL 6 to TRL 7

This Test Plan is organized according to Design Data Need. The required data need to be obtained for the reactor service conditions during normal operation and accident conditions. These conditions are defined in the NGNP Umbrella Technology Development Plan [Hanson 2007] and include temperature, pressure, fast neutron fluence, and coolant impurity levels. For some tests, it may be impractical to obtain data under the specified NGNP conditions, and methodologies to extrapolate the data from test conditions to reactor conditions must be developed before the specific Test Specifications and Test Plans are approved.

4.1 Core Column Vibration Data (DDN C.11.03.01)

4.1.1 Test Objective

The objective of this test program is to verify that there are no significant flow induced vibrations of the core columns in the NGNP annular prismatic core under any reactor operating conditions and to validate computer codes and methods for predicting core column vibrations.

4.1.2 Test Description

The purpose of this test is to validate that the 10-block high active core design and associated reflectors of the NGNP are dynamically stable to aerodynamic excitation which could cause impact loads on the blocks and adversely affect their structural integrity. This will be achieved by conducting vibratory test on subscale models of one or more core columns of fuel and reflector elements, with and without modifications to inhibit vibration.

4.1.3 Test Conditions

The test will be performed on unirradiated elements under ambient conditions.

4.1.4 Test Configuration/Set-Up

Two models are envisioned. These will be tested in two separate phases. They will all be 3-D models, and will represent a single column of fuel and reflector blocks (Phase I), and a sector of multiple core columns in the core (Phase II). If tests from Phase I demonstrate with confidence that flow induced vibration is understood sufficiently to ensure that the core design is satisfactory then Phase II will not be conducted.

The purpose of the single-column model test is to provide basic understanding of the mechanical and aerodynamic aspects of a single core or reflector column. This will be used as basis for designing the Phase II multicolumn test as well as to support and guide the analytical effort. A subscale core column model with various geometric constraints will be mechanically excited to study its vibratory characteristics. The model shall be housed in an enclosure to simulate the boundary interfaces of the adjacent core columns.

4.1.5 Test Duration

30 months, including preparation of all test documentation

4.1.6 Proposed Test Location

The testing could be performed at GA, the Component Test Facility (CTF), a National Laboratory, or at a commercial material testing facility.

Commercial Material Testing Laboratory Contact:
Envibe Condition Monitoring

4140 Directors Row, Suite H

Houston, TX 77092

Phone: 1-888-473-5222 Fax: 713-682-8771

4.1.7 Measured Parameters

The vibratory characteristics sought are fundamental frequencies (25 Hz or less) and the associated modal shapes and damping factors. The excitation shall be mechanically induced. The kinematical parameters to be evaluated are as follows

<u>Gap Size and Distribution</u>
The gap between two core graphite blocks can vary from near zero to a maximum of [TBD]. The gap distribution can be concentric as well as eccentric.

<u>End Support</u>
The lower end support shall at least consist of two cases. The first case has a T-post support simulating an active core column or an inner side reflector column. The second case simulates an outer side reflector column stacked from the floor up to the plenum element elevation. The upper end support shall be representative of the conceptual plenum element configuration. Other idealized end conditions, such as fixed and pinned, etc., although of only theoretical interest, shall also be examined. This will be used to calibrate the theoretical calculation and, possibly, to guide the designer to some design improvements that may stabilize the core column.

<u>Axial Load</u>
The effect of the: axial load to the vibratory response shall be examined.

<u>Intermediate Support</u>
An intermediate (horizontal) support to the single column will alter the vibratory responses and will be tested.

The effects of block distortions will also be evaluated.

The vibratory characteristics shall be assessed in three distinct regions for each combination of the above parameter. In the first region, the model acts like: a continuous elastic beam with no breaking at any two adjacent block interface and no touching of the enclosure sidewall. In the second region, two adjacent blocks break and have relative rotation at the interface. In the last region, the column not only breaks at some time point, and it also touches the boundary sidewall. The last two regions depend on the gap size and its distribution.

Following the aforementioned mechanical excitation of the single column model, the model shall also be excited aerodynamically. The dynamical parameters to vary are as follows:

- Axial Gap Flow Rate
- Axial Internal Flow in a Column
- Jaw Flow Out of the Single Column
- Jaw Flow Impinging Upon the Single Column
- Axial Bypass Flow in the Control Rod or RSS Holes
- Block Distortions

In the aerodynamically excited test phase, in combination with the dynamic parameters, selected kinematic parameters shall be parametrically studied over the range of interest to investigate if any coupling effect exists.

4.1.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.”

4.1.9 Test Evaluation Criteria

To be determined by the Design and Technology Organizations

4.1.10 Test Deliverables

Deliverable	Responsibility
Test Specification	Design Organization
Test Plan	Technology Organization
Test Procedures	Technology Organization
Pre-Test Prediction Report	Design Organization
Test Status Reports	Technology Organization
Test Report	Technology Organization
Test Evaluation Report	Design Organization

4.1.11 Cost, Schedule, and Risk

Cost (2008 $K): 2,500

Schedule: Final data are needed 24 months before the start of NGNP startup testing

Risk

In the absence of obtaining vibration data, the design alternative is to design the core and the supports to minimize the potential for vibrations, and continue to use the current design analysis methods and data base without further validation. The selected approach is to validate by test using scaled models. The consequences of not obtaining the data could be that it would be necessary to redesign the core restraint system, if excessive vibration were encountered at reactor startup, which would result in schedule delays and cost increases.

4.2 Core Crossflow Test Data (DDN C.11.03.45)

4.2.1 Test Objective

The objective of this test program are to obtain data to characterize the flow exchange at core elements interfaces between the coolant channels and the surrounding gaps between columns (crossflow) to meet the requirements for control rod temperatures, fuel element stresses, and fuel temperatures.

4.2.2 Test Description

The tests comprise three column types: standard fuel column, reserve shutdown fuel column and reflector control rod column. Six blocks will be included in each column. The blocks will be full scale. The test will be contained in a structure simulating the gaps between the columns in the core array. The assembled test components will be attached to an air flow source. Gap pressure and temperature, pressures and flow rates in the coolant channels and gaps and a means of tracking the cross flow (e.g., using helium dopant and measuring the helium gas concentration at downstream locations) will be measured.

4.2.3 Test Conditions

The tests will be conducted with air at ambient conditions per the criteria shown below:

Criteria	Maximum Value	Minimum Value
Cross flow gap width (in.)	0.2	0
Gap Reynolds number	15,000	0
Channel/gap pressure differential (psi)	2.0	0
Coolant channel Reynolds number	100,000	0

4.2.4 Test Configuration/Set-Up

The assembled test components will be attached to the air flow source. The air flow source will have a variable speed electric drive motor. The air mass flow will be varied to provide the range of Reynolds numbers given above. Gap pressure and temperature, pressures and flow rates in the coolant channels and gaps and a means of tracking the cross flow (i.e. using helium dopant and measuring the helium gas concentration at downstream locations) will be measured.

4.2.5 Test Duration

30 months, including preparation of all test documentation

4.2.6 Proposed Test Location

The testing could be performed at GA, the Component Test Facility (CTF), or a National Laboratory.

4.2.7 Measured Parameters

Data are needed for loss coefficients for standard, reserve shutdown, and reflector control rod block crossflow gaps as a function of expected crossflow pressure differentials, crossflow gaps, and coolant and bypass gap Reynolds numbers under the conditions given above.

4.2.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, "Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development."

4.2.9 Test Evaluation Criteria

The data base must be sufficient such that the friction factors can be estimated with an accuracy of [± 10%] at [95%] confidence.

4.2.10 Test Deliverables

Deliverable	Responsibility
Test Specification	Design Organization
Test Plan	Technology Organization
Test Procedures	Technology Organization
Pre-Test Prediction Report	Design Organization
Test Status Reports	Technology Organization
Test Report	Technology Organization
Test Evaluation Report	Design Organization

4.2.11 Cost, Schedule, and Risk

Cost (2008 $K): 1,000

Schedule: Final data are needed 24 months before the start of NGNP startup testing.

Risk

In the absence of obtaining crossflow data, the design alternative is to continue to rely on the currently available data and allow for greater design margins. Consequences of not obtaining the data are difficulty in meeting the stress and temperature limits, a potential increase in fuel failure and increased difficulty in meeting fission product release limits.

4.3 Core Fluctuation Test Data (DDN C.11.03.46)

4.3.1 Test Objective

Core fluctuation is the periodic movement of individual columns or groups of columns in the core resulting from thermal/hydraulic interaction. Core fluctuations result from the following scenario: A column leans in one direction which causes a reduction of cooling gas flow through the adjacent gap in that direction. That side of the column becomes hotter than the other side, and expands, and the column bows. The bowing of the column causes a redistribution of cooling gas flow and the gas pressures on the vertical surfaces of the column, and the column moves to a new stable position, leaning in another direction. The uneven cooling, thermal distortion, redistribution of flow and gas pressure is then repeated, and after some time another movement takes place.

The objective of this test program is to validate the 10 block high active core and associated reflectors are stable to mechanical and thermal movements which would cause fluctuations in the outlet coolant temperatures. Data will be taken to validate that the core array will be stable and not adversely affected by the expected heating, flow and pressure drop conditions. The data will be used to validate computer codes and methods.

4.3.2 Test Description

Fluctuation tests on scale models of one or more core columns of fuel and reflector elements, with and without modifications to inhibit fluctuations will be conducted.

4.3.3 Test Conditions

To be determined by the Design and Testing Organizations.

4.3.4 Test Configuration/Set-Up

Three models are envisioned to be tested in three separate phases. They will all be 3-D models, and will represent a single column of fuel and reflector blocks, 9 columns (i.e., a typical 30 deg. segment of the active core), and 102 columns (i.e., the number of columns in the annular active core).

A model of a single column of core fuel and reflector blocks will be tested first to support the conceptual design of the NGNP core. During the first phase of testing, the effect of the following parameters will be evaluated: (1) Gap size and distribution (2) Block and column shape (to simulate thermal and irradiation distortion); (3) Flow rate and pressure drop; (4) Restricted motion of the top and bottom reflector element; (5) Heating rate; and (6) Number of blocks in the column.

Subsequent models having multiple columns will be used to quantify the interaction between columns and prove the effectiveness of the NGNP core design to suppress core fluctuations. If data are sufficient from the 9 column model to ensure stability, testing of the 102 column model will not be performed.

The flow and thermal conditions in the reactor core will be simulated in the models using air at ambient conditions at the inlet and electrically heated fuel elements to simulate nuclear heating in the core. All the models proposed will dimensionally represent the reactor fuel column at ¼ scale. This scale is small enough to permit easy and economical fabrication, assembly, and handling of the models, yet it is large enough so that test results which are greatly affected by gap dimensions and block distortions are not being influenced by manufacturing tolerances. The models will be made of materials having properties which can simulate the thermal distortion of the columns with small temperature variations.

4.3.5 Test Duration

30 months, including preparation of all test documentation

4.3.6 Proposed Test Location

The testing could be performed at GA, the Component Test Facility (CTF), or a National Laboratory.

4.3.7 Measured Parameters

The data required includes fundamental data such as core pressure drop, core heating rate, coolant flow rate, coolant pressure, and coolant temperature. In addition, block temperatures,

block distortions, and pressure forces on the blocks shall be recorded. Finally, records shall be made of when fluctuations occur, the frequency of fluctuations, and the impact forces on the blocks resulting from fluctuations.

4.3.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.”

4.3.9 Test Evaluation Criteria

To be determined by the Design and Technology Organizations.

4.3.10 Test Deliverables

Deliverable	Responsibility
Test Specification	Design Organization
Test Plan	Technology Organization
Test Procedures	Technology Organization
Pre-Test Prediction Report	Design Organization
Test Status Reports	Technology Organization

Test Report	Technology Organization
Test Evaluation Report	Design Organization

4.3.11 Cost, Schedule, and Risk

Cost (2008 $K): 5,000

Schedule: Final data are needed 24 months before the start of NGNP startup testing

Risk

In the absence of obtaining core fluctuation data, the design alternative is to design the core and the supports to minimize temperature fluctuations and rely on the current data base and analytical predictions for validation of the absence of core fluctuations. The selected approach is to validate the design using scaled-model testing. Consequences of not obtaining the data include unexpected core fluctuations during startup testing, which could require additional design measures, delay the schedule, and increase costs.

4.4 Bottom Reflector/Core Support Pressure Drop and Flow Mixing Data (DDN C.11.03.43)

4.4.1 Test Objective

Confirmation is required that the following limits are met: core pressure drop, maldistribution of coolant channel flows in the columns, the temperature of the coolant entering the hot duct, and the temperature of hot and cold streaks entering the hot duct. The objective of this test is to obtain data to validate computer codes and methods for predicting these parameters.

4.4.2 Test Description

This test will be performed on a mock-up of the NGNP core bottom structure. The test will be better defined after additional NGNP design work has been performed.

4.4.3 Test Conditions

To be determined after additional design work on the NGNP has been performed. A determination will be made as to whether both cold and hot testing needs to be performed.

4.4.4 Test Configuration/Set-Up

This test will be performed on a scaled mock-up of the NGNP core bottom structure. A potential configuration is shown in Fig. 3-1.

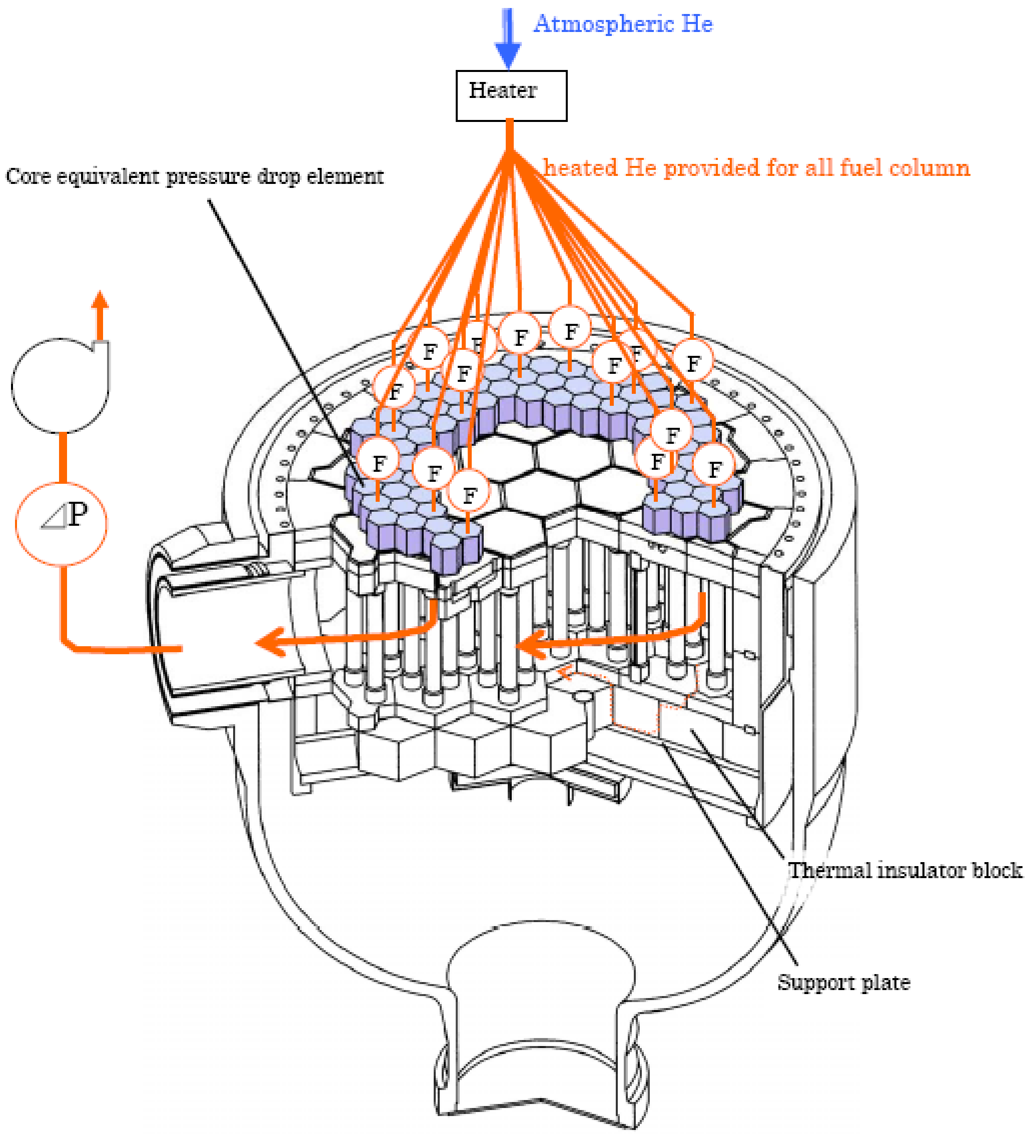

Figure 3-1. Potential Configuration for Mock-up testing of Core Bottom Structure

4.4.5 Test Duration

30 months, including preparation of all test documentation

4.4.6 Proposed Test Location

GA, the CTF, or commercial test facilities

4.4.7 Measured Parameters

Pressure drop, maldistribution of coolant channel flows in the columns, the temperature of the coolant entering the hot duct, and the temperature of hot and cold streaks entering the hot duct.

4.4.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.”

4.4.9 Test Evaluation Criteria

To be determined by the Design and Technology Organizations.

4.4.10 Test Deliverables

Deliverable	Responsibility
Test Specification	Design Organization
Test Plan	Technology Organization
Test Procedures	Technology Organization
Test Status Reports	Technology Organization
Test Report	Technology Organization
Test Evaluation Report	Design Organization

4.4.11 Cost, Schedule, and Risk

Cost (2008 $K): 5,500

Schedule: Final data are needed 24 months before the start of NGNP startup testing

Risk

In the absence of obtaining this data, the design alternative is to use the loss coefficient estimates based on data in the general literature and to estimate mixing. The selected approach is to determine the pressure loss coefficients, flow distribution, and hot/cold streak attenuation by testing. Relying on estimates based on available data and engineering judgment would provide less confidence in the results. Also, testing may identify modifications to reduce pressure drop and/or improve flow distribution or hot/cold streak attenuation. Consequences of not obtaining the data are a less optimized design; allowance for higher core pressure drop in the circulator design, higher hot/cold streaks exiting the core, and greater flow maldistribution in the fuel columns.

4.5 Metallic Plenum Element and Top Reflector Pressure drop and Flow Distribution (DDN C.11.03.44)

4.5.1 Test Objective

The objective of this test is to obtain data to validate computer codes and methods for predicting the flow distribution and pressure drop in the upper plenum and top reflector elements.

4.5.2 Test Description

This test will be performed on a mock-up of the NGNP core upper structure. The test will be better defined after additional NGNP design work has been performed.

4.5.3 Test Conditions

To be determined after additional design work on the NGNP has been performed. A determination will be made as to whether both cold and hot testing needs to be performed.

4.5.4 Test Configuration/Set-Up

This test will be performed on a scaled mock-up of the NGNP core upper structure.

4.5.5 Test Duration

30 months, including preparation of all test documentation

4.5.6 Proposed Test Location

GA, the CTF, or commercial test facilities

4.5.7 Measured Parameters

Pressure drop and maldistribution of coolant channel flows in the columns.

4.5.8 Data Requirements

All work performed to support the NGNP R&D Program will be in accordance with The Next Generation Nuclear Plan (NGNP) Quality Assurance Program, INEEL/EXT-04-01776, and will utilize the national consensus standard ASME NQA 1997, "QA Program Requirements for Nuclear Facilities Applications," and Subpart 4.2 of ASME NQA 2000, “Guidance on Graded Application of Quality Assurance (QA) for Nuclear-Related Research and Development.”

4.5.9 Test Evaluation Criteria

To be determined by the Design and Technology Organizations

4.5.10 Test Deliverables

Deliverable	Responsibility
Test Specification	Design Organization
Test Plan	Technology Organization
Test Procedures	Technology Organization
Test Status Reports	Technology Organization
Test Report	Technology Organization
Test Evaluation Report	Design Organization

4.5.11 Cost, Schedule, and Risk

Cost (2008 $K): 5,500

Schedule: Final data are needed 24 months before the start of NGNP startup testing

Risk

In the absence of obtaining this data, the design alternative is to use the loss coefficient estimates based on data in the general literature and to estimate flow distributions. The selected approach is to determine the pressure loss coefficients and flow distribution by testing. Relying on estimates based on available data and engineering judgment would provide less confidence in the results. Also, testing may identify modifications to reduce pressure drop and/or improve flow distribution. Consequences of not obtaining the data are a less optimized design; allowance for higher core pressure drop in the circulator design, higher hot/cold streaks exiting the core, and greater flow maldistribution in the fuel columns.

5 TEST PLAN FOR ADVANCEMENT FROM TRL 7 to TRL 8

To achieve a TRL of 8, instrumented tests are performed as part of NGNP startup testing to confirm flow distributions, temperature distributions, and mechanical loadings are within design specifications.

This plan will be developed in more detail during the preliminary and final design phases.

6 SCHEDULE

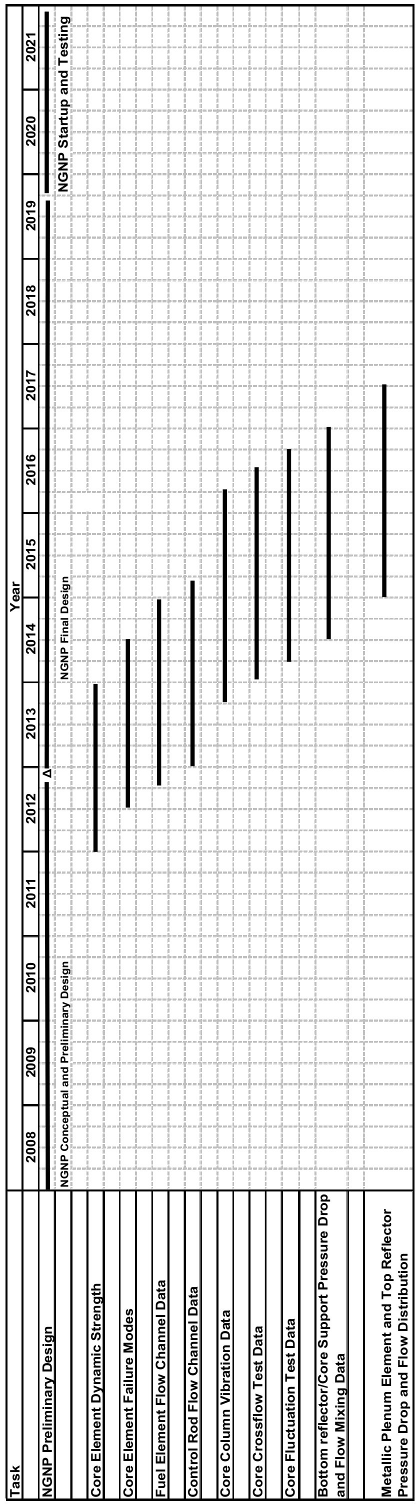

Figure 5-1. Overall Schedule for Reactor Core Test Program

GENERAL ATOMICS

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